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14. ABSTRACT
Objective: The aim of this study was to examine the effects of uncertainty about where in the field of view critical signals for detection appear during a vigilance task (spatial uncertainty) on cerebral blood flow velocity (CBFV) and oculomotor fatigue. **Background:** Neuroergonomics is a dimension of human factors founded by Raja Parasuraman that studies brain functions underlying performance at work. Neuroergonomic studies have shown that observers in vigilance tasks lose information processing resources over time and experience oculomotor fatigue as indexed by a temporal decline in CBFV and elevation in eye closure as reflected in the PERCLOS metric. Because spatial uncertainty increases an observer's need for visual scanning relative to a spatial certainty condition, it was anticipated that spatial uncertainty would result in a greater temporal decline in CBFV and increased eye closure in a vigilance session. **Method:** Observers performed a simulated unmanned aerial vehicle (UAV) control task wherein collision flight paths were the events to be detected. UAV images could appear at random in any one of five locations on the controller's display (spatial uncertainty) or only in a fixed location (spatial certainty). **Results:** Signal detection was poorer in the spatial uncertain relative to the certain condition, and predictions regarding CBFV and eye closure were confirmed. **Conclusion:** Vigilance tasks involving spatial uncertainty are more neurophysiologically taxing than those in which spatial uncertainty is not a factor. **Application:** The neuroergonomic approach helps in understanding the effects of psychophysical factors in vigilance and to signify when performance aiding is needed.

15. SUBJECT TERMS
neuroergonomics, vigilance, spatial uncertainty, cerebral hemovelocity, transcranial Doppler sonography, oculomotor fatigue

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The Neuroergonomics of Vigilance: Effects of Spatial Uncertainty on Cerebral Blood Flow Velocity and Oculomotor Fatigue

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Results: Signal detection was poorer in the spatial-uncertain relative to the certain condition, and predictions regarding CBFV and eye closure were confirmed.

Conclusion: Vigilance tasks involving spatial uncertainty are more neurophysiologically taxing than those in which spatial uncertainty is not a factor.

Application: The neuroergonomic approach helps in understanding the effects of psychophysical factors in vigilance and to signify when performance aiding is needed.

Keywords: neuroergonomics, vigilance, spatial uncertainty, cerebral hemovelocity, transcranial Doppler sonography, oculomotor fatigue

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INTRODUCTION

A poignant element in Raja Parasuraman's legacy to the field of human factors is his concept of neuroergonomics, the study of the brain and behavior at work, which merges cognitive neuroscience and human factors research (Parasuraman, 2003, 2011; Parasuraman & Rizzo, 2007; Rizzo & Parasuraman, 2015). In this investigation we focused on two neuroergonomic dimensions, cerebral blood flow velocity (CBFV) and oculomotor fatigue, to understand the effects of uncertainty in regard to the spatial location of critical-signal appearances on the performance efficiency of observers in a vigilance, or sustained attention, task. Tasks of this sort concern the ability of observers to detect infrequent and unpredictable stimulus events over extended periods. They are of interest to human factors specialists because they are a crucial aspect of many work environments wherein automated systems are featured, including aviation, airport/border security, seaboard navigation, military surveillance, industrial process control, and medical monitoring/screening (Reinerman-Jones, Matthews, & Mercado, 2016; Small, Wiggins, & Loveday, 2014; Thomson, Besner, & Smilek, 2015; Warm, Finomore, Vidulich, & Funke, 2015).

A pervasive finding in experiments on vigilance is the progressive decline in performance efficiency with time on task, known as the decrement function or the vigilance decrement (Davies & Parasuraman, 1982; Matthews, Davies, Westerman, & Stammers, 2000; Warm et al., 2015). Several studies have employed a noninvasive neuroimaging procedure known as transcranial Doppler sonography (TCD) to reveal neurophysiological changes that accompany the vigilance decrement and also variations in the information-processing

demands of vigilance tasks. As described by Tripp and Warm (2007), TCD utilizes ultrasound signals to monitor CBFV in the mainstem intracranial arteries—the middle (MCA), anterior, and posterior arteries. TCD measures the difference in frequency between outgoing and reflected energy as it strikes moving erythrocytes. The vigilance studies to be described later have exclusively used measures taken from the MCA because it carries approximately 80% of the blood to each cerebral hemisphere (Netter, 1989).

When a particular area of the brain becomes metabolically active, as in mental task performance, by-products of this activity, such as carbon dioxide (CO_2), increase. This increase in CO_2 leads to increased blood flow to the region to remove the unwanted by-products (Aaslid, 1986; Hellige, 1993). Consequently, TCD offers a way to measure changes in metabolic activity during task performance (Duschek & Schandry, 2003; Stroobant & Vingerhoets, 2000; Tripp & Warm, 2007). It should be noted that the elevation in blood flow may also serve to deliver needed glucose and oxygen, but that possibility is open to question (Mintun et al., 2001; Raichle, 1987, 1998; Tripp & Warm, 2007).

Researchers using TCD have found that the vigilance decrement is paralleled by a temporal decline in CBFV that generalizes across sensory modalities, is amplified by the cognitive demands of the task, and is most notable in the right hemisphere, pointing to a right-hemispheric system in control of vigilance. In addition, it was demonstrated in these studies that the temporal decline in CBFV occurs only when observers actively engage in processing task-related information; cerebral hemovelocity remains stable over time when observers are exposed to a vigilance task without a work imperative (Greenlee et al., 2015; Hollander et al., 2004; Parasuraman, Warm, & See, 1998; Rizzo & Parasuraman, 2015; Shaw, Finomore, Warm, & Matthews, 2012; Shaw et al., 2009, 2013; Warm, Matthews, & Finomore, 2008; Warm, Matthews, & Parasuraman, 2009; Warm & Parasuraman, 2007; Warm, Parasuraman, & Matthews, 2008; Warm, Tripp, Matthews, & Helton, 2012).

As described by Ross, Russell, and Helton (2014), Shaw et al. (2013), and Warm et al. (2015), these studies have been viewed as supporting a model of vigilance proposed by Raja Parasuraman and Roy Davies (Davies & Parasuraman, 1982; Parasuraman & Davies, 1977) that is anchored in a general view of attention known as resource theory (Kahneman, 1973; Wickens, Hollands, Banbury, & Parasuraman, 2013) and the concepts of task overload and cognitive fatigue (Lorist & Faber, 2011; Thomson et al., 2015; Warm et al., 2012). According to this model, a limited-capacity information-processing system allocates resources or information-processing assets to deal with situations that confront it. Cognitive fatigue in vigilance task performance is induced by the need to make continuous signal/noise discriminations over time and the consequent depletion of information-processing assets that cannot be replenished during time on task. As a result, signal detection declines. The associated drop-off in CBFV is assumed to reflect the reduction in information-processing resources. As Warm, Parasuraman, and Matthews (2008) have noted, when viewed in this way, the CBFV measure insulates the resource model from the criticism of circular reasoning attendant with inferring resource changes only from performance (cf. Navon, 1984). The resource model of vigilance proposed by Raja Parasuraman and Roy Davies was the source of predictions regarding performance and CBFV changes in this study.

It is noteworthy that in all of the previous CBFV/vigilance studies, neutral and critical stimulus events appeared in a fixed portion of the visual field and observers did not have to scan wide areas of the field in order to detect their presence. However, spatial uncertainty, or uncertainty as to exactly where signals for inspection will appear, can be a key factor in many operational vigilance tasks. In air traffic control, for example, the aircraft to be monitored do not appear at only a single position on a radar display. Consequently, spatial uncertainty has been considered as one of the major psychophysical factors influencing information processing in vigilance tasks (Davies & Parasuraman, 1982; Matthews et al., 2000; Warm et al., 2015; Warm & Jerison, 1984). Given that an understanding of the neurophysiology underlying the effects of psychophysical factors in vigilance is a key element in the neuroergonomic approach to vigilance, an examination of the

effects of spatial uncertainty on CBFV was a major concern in this study.

In view of the greater need for visual scanning in the context of spatial uncertainty as compared to spatial certainty, and that the need to scan visual space is taxing on an observer's resources (Johnson & Proctor, 2004; Jonides, 1981), it might be anticipated from resource theory that performance efficiency would be poorer in the uncertainty context. This is indeed the case. In an illustrative study, Milosevic (1974) asked observers to detect increments in the intensity of flashing lights located in the center and at the four corners of a square. Observers were required only to monitor the center light in the spatial-certainty condition, whereas they were required to monitor all five of the lights in a spatial-uncertainty condition. Performance efficiency was poorer in the latter case. Adams and Boulter (1964); Baker (1958); Bell, Symington, and Bevan (1974); Grubb, Warm, Dember, and Berch (1995); Helton, Weil, Middlemiss, and Sawers (2010); Kulp and Alluisi (1967); Mouloua and Parasuraman (1995); and Nicely and Miller (1957) have also found that spatial uncertainty degrades the efficiency of signal detection in vigilance tasks. One issue that comes up in regard to these findings is whether they were actually related to uncertainty rather than just the need to perform a central versus noncentral task. To address that issue, Adams and Boulter (1964) presented stimuli in a consistent or predictable series across locations and in an inconsistent unpredictable series and found that performance was poorer in the latter as compared with the former condition, indicating that uncertainty was indeed an important factor in studies of this sort.

One goal for the present study was to test the expectation, based on resource theory, that because of the higher information-processing demands associated with spatial uncertainty, the decline in CBFV over time would be greater when observers were uncertain about where in the visual field events to be inspected would appear (spatial uncertainty) than when those events occurred in a fixed location (spatial certainty). Consistent with previous findings regarding a right-hemispheric system in the control of vigilance, it was also anticipated that the CBFV effects associated with spatial uncertainty would be most noticeable in the right cerebral hemisphere.

Another neuroergonomic dimension that has been employed to aid in understanding human performance is oculomotor activity (Holmqvist et al., 2011; Kramer & McCarley, 2003; McCarley & Kramer, 2007; Seagull, 2015; Stern, Boyer, & Schroeder, 1994; Wickens et al., 2013; Wilson & O'Donnell, 1988). Of particular concern in the present study was the PERCLOS measure, which gauges the percentage of time during task performance when 75% or more of each of an observer's eyes is simultaneously covered by the individual's eyelids (Wierwille, Ellsworth, Wreggit, Fairbanks, & Kim, 1994). Several researchers have shown that the percentage of eye closure increases with fatigue during driving tasks (Hanowski, Wierwille, Gallatly, Early, & Dingus, 2000; Marquart, Cabrall, & de Winter, 2015; Senaratne, Hardy, Vanderaa, & Halhamuge, 2007; Wylie, Shultz, Miller, Mitler, & Mackie, 1996), and Dinges, Mallis, Maislin, and Powell (1998) have reported a similar effect during performance of the psychomotor vigilance task, a task that is frequently employed in fatigue research.

As with CBFV and vigilance, oculomotor fatigue has not been examined with regard to the effects of spatial uncertainty. Accordingly, a second goal for the present study was to compare the effects of spatial uncertainty and spatial certainty conditions in a vigilance task on the percentage of eye closure. As in the case of CBFV, resource theory led us to anticipate that the PERCLOS index would increase with time on task and that the higher information processing demands associated with spatial uncertainty relative to spatial certainty would lead this effect to be greater in the context of spatial uncertainty than certainty.

METHOD

Participants

The study was carried out at the Air Force Research Laboratory, Wright-Patterson Air Force Base (WPAFB). Thirty-six participants (19 men and 17 women) were recruited from base personnel and the local population to serve as observers for a single payment of $30. They ranged in age from 18 to 29 years with a mean of 21.5 years. As indicated by self-report, all observers had normal or corrected-to-normal

vision, had normal hearing, and were right-handed. They were required to abstain from caffeine, nicotine, and medication for 12 hr prior to participating in the study (Stroobant & Vingerhoets, 2000). All of the observers met that requirement. The project was approved by the WPAFB Institutional Review Board.

Experimental Design

Twelve observers (six men and six women) were assigned at random to each of two active vigilance conditions defined by the spatial certainty or uncertainty in the vigilance display to be monitored. An additional 12 participants (five men and seven women) served as passive control observers to ensure that temporal changes in CBFV were task determined.

VIGILANCE TASKS

Observers in the active vigilance conditions participated in a 50-min vigilance session composed of five continuous 10-min periods. The vigilance displays employed in this study were adapted from those utilized in three earlier studies in this laboratory (Dillard et al., 2014; Funke et al., 2011; Shaw et al., 2013). In the active vigilance conditions, participants assumed the role of unmanned aerial vehicle (UAV) controllers monitoring the flight pattern of a squadron of four UAVs projected on a 43.18-cm visual display terminal (VDT). As illustrated in Figure 1, the display consisted of five open circular viewing fields (9.53 cm in diameter) banded by a black border that was presented on a gray background (transluminance = 42 cd/m^2). Each viewing field consisted of three concentric circles, the smallest measuring 2.54 cm in diameter, the middle circle measuring 6.35 cm in diameter, and the largest formed by the exterior black circle. Each field was divided into four equal 90° quadrants defined by black lines. In all cases, the defining lines were 0.32 cm thick, and their contrast with the gray background based upon the Michaelson contrast ratio (Coren, Ward, & Enns, 1999) was 6.32%. A visual angle of 18.76° separated the centers of the four peripheral viewing fields from each other, and a visual angle of 13.50° separated the center of the central viewing field from each of the peripheral viewing fields. Normally the viewing fields were inactive and all their quadrants were blank, as shown in Figure 1.

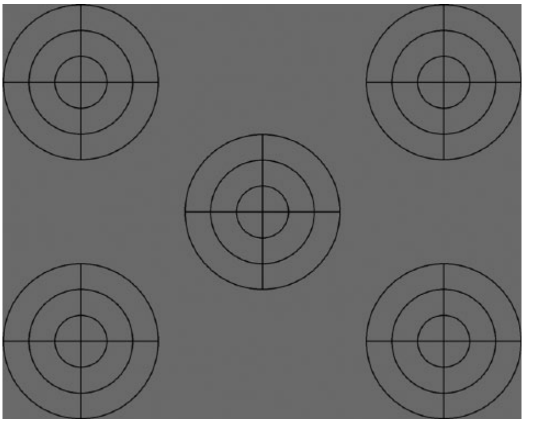

Figure 1. Inactive viewing fields for all conditions.

Stimulus events that needed to be inspected were cases in which one of the viewing fields was activated. In such cases, each quadrant of the activated field contained a black triangular icon (base = 1.35 cm, altitude = 0.95 cm, transluminance = 37 cd/m^2, contrast with gray background = 6.32%), which represented a UAV. In all conditions, static images were presented to observers throughout the vigil. The images depicted the UAV squadron flying in either a clockwise or a counterclockwise direction, as defined by the "noses" of the aircraft. The UAVs were oriented in a clockwise direction for half of the participants in each active condition and in a counterclockwise direction for the other half. The directions were determined at random for each participant with the restriction that they occurred equally often across the 12 participants in each active condition. Critical signals for detection were cases in which one of the UAVs was oriented in the opposite direction of its cohorts, implying that a collision could occur. Neutral events and critical signals in both flight directions are illustrated in Figure 2.

In the *spatially certain* condition, all neutral events to be inspected for critical signals were presented only within the center viewing field, and scanning the five viewing fields was unnecessary. In this condition, the center field was updated 30 times per minute with a dwell time of 1,000 ms within each period of watch. In the

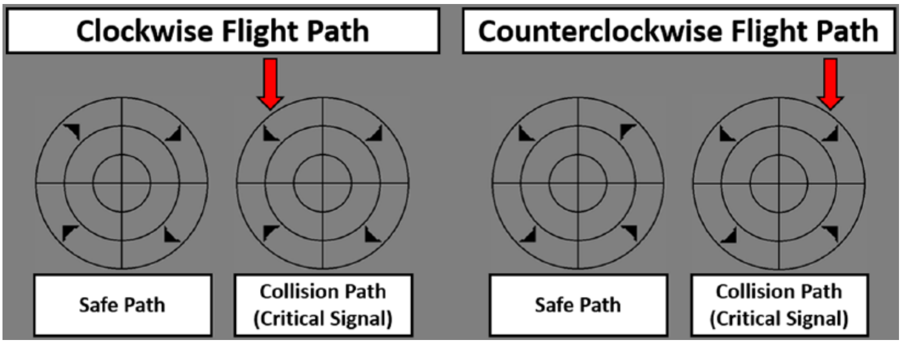

Figure 2. Examples of neutral events and critical signals in the flight path display (adapted from Dillard et al., 2014; Funke et al., 2011; and Shaw et al., 2013).

spatially uncertain condition, the squadron of UAVs would appear randomly within any one of the five viewing fields on the display terminal with the restriction that each of the viewing fields was activated for 1,000 ms six times per minute within each period of watch. Thus, the overall event rate was equated in both viewing conditions, and the frequency of activation of the five viewing fields was equated in the spatially uncertain condition. In both active conditions, 20 critical signals occurred at random intervals during each period of watch (signal probability per period = 6.67%). Five critical signals appeared in each display quadrant of the center field per period in the spatially certain condition. In the spatially uncertain condition, one critical signal appeared in each of the four display quadrants of each of the five viewing fields per period. Observers indicated their detection of critical signals by pressing the space bar on a computer keyboard. Responses occurring within 1,000 ms of the onset of critical signals were recorded automatically as correct detections. All other responses were recorded as errors of commission or false alarms. The lack of a response to a critical signal was recorded as a miss.

Observers in the passive control condition viewed the flight display for 40 min (see Procedure below for justification of their abbreviated vigil) but without an information-processing imperative. These observers were not provided with a definition of critical (collision path) and neutral (safe path) events, nor were they given any information about pressing keys on the keyboard. They were instructed to simply gaze at the display until the session ended. Six passive observers were assigned at random to view the spatially certain and six the spatially uncertain versions of the flight path display (including the appropriate neutral and critical events), with half of the observers in each version exposed to the clockwise UAV flight path and the remainder to the counterclockwise flight path.

CBFV and Oculomotor Measurement

Within the two active flight conditions and the passive control condition, bilateral hemovelocity measurements were taken from the left and right MCAs of all observers using a Nicolet Companion III TCD unit equipped with 2 MHz ultrasound transducers. The transducers were embedded in a plastic bracket and secured to the observer's head by an adjustable plastic strap. They were located dorsal and immediately proximal to the zygomatic arch along the temporal bone on either side of the skull. A dab of Aquasonic-100 brand ultrasound transmission gel was placed on the transducers to ensure transmission of the ultrasound signal. The distance between the transducer on the skin and the sample volume could be adjusted in 2-mm increments in order to isonate the MCA, which was generally monitored at depths of 50 to 55 mm. Hemovelocity measures (in cm/s) were averaged and recorded automatically by the TCD unit at approximately 1 Hz.

Oculomotor data were collected using a Seeing Machines Inc. faceLAB 4.0 eye-tracking system.

The system, mounted immediately below the VDT, consisted of two infrared cameras and a group of infrared light–emitting diodes. The cameras recorded eye movements at a rate of 60 Hz using corneal reflectance to gauge eyelid closure.

Procedure

Upon reporting for the experiment, all observers participated in a 5-min resting baseline phase during which the CBFV measure was recorded while they were seated in front of a blank VDT. Observers were asked to refrain from talking and to minimize body movement while breathing normally and maintaining relaxed wakefulness (Tripp & Warm, 2007).

Individual testing was conducted in a 1.78 × 2.41 × 2.67-m windowless laboratory room. The VDT was mounted on a table 99.10 cm directly in front of the seated observer (visual angle = 23.54°). Ambient illumination in the testing room (5 cd/m^2) was provided by a single 50-watt incandescent bulb reduced to half power and positioned above and behind the seated observer in order to minimize glare on the VDT. To curb distraction, observers were separated from the TCD equipment by a cubicle wall dividing the width of the testing room in half.

Upon completing the resting baseline phase, observers in the active conditions were instructed as to the nature of the task they were to perform. The vigil was initiated immediately thereafter. Critical signals for detection in the collision display employed herein were difficult to discern. Consequently, following a procedure utilized in one of our previous studies with this display (Shaw et al., 2013), a computerized female voice provided feedback as to correct detections, misses, and false alarms to all active observers during the initial 10-min period of the task. Observers were required to detect at least 60% of the critical signals and make no more than 10 false alarms in this period of watch for their data to be included in the final analysis. All active observers met this dual criterion. Beginning with minute 11, audio feedback was removed and observers completed the vigil in silence.

Observers in the passive control condition initiated observation of the vigilance display immediately after the resting baseline phase. As they did not need to actively interact with the display, they did not require task instruction or initial performance feedback. Therefore, the passive observers viewed the display in a 40-min session divided into four continuous 10-min periods.

All observers surrendered timepieces and cell phones upon entering the laboratory and had no knowledge about the length of the experimental session other than it would not exceed 120 min.

RESULTS

Performance Efficiency

Detection probability. Mean percentages of correct detections for the spatially certain and the spatially uncertain conditions are presented as a function of periods of watch in Figure 3 along with the overall period means.

It is apparent in the figure that the observers in the spatially certain condition outperformed their counterparts in the spatially uncertain condition and that the detection scores in both conditions declined over time. To test these impressions, the percentages of correct detections for both conditions were converted to arcsines (Kirk, 1995) and tested for significance by means of a 2 (conditions) × 5 (periods of watch) mixed-model analysis of variance (ANOVA). The analysis revealed significant main effects for condition, $F(1, 22) = 9.78$, $p < .05$, $\eta_p^2 = .31$, and periods of watch, $F(2.63, 57.75) = 8.68$, $p < .05$, $\eta_p^2 = .28$. The interaction between these factors was not significant, $p > .05$. In this and all subsequent ANOVAs, Box's epsilon was employed when needed to correct for violations of the sphericity assumption (Maxwell & Delaney, 2004).

The overall vigilance decrement reflected in the main effect for periods, also displayed in Figure 3, had significant linear, $F(1, 22) = 7.95$, $p = .01$, $\eta_p^2 = .26$, and quadratic, $F(1, 22) = 23.54$, $p < .001$, $\eta_p^2 = .52$, components supporting the view that the overall percentage of correct detections declined consistently from Periods 1 to 3 and then leveled off.

Errors of commission, that is, false alarms, were infrequent in this study. The mean false-alarm rate in each of the spatial conditions was less than 1% throughout the vigil. Consequently, false alarms were not analyzed further.

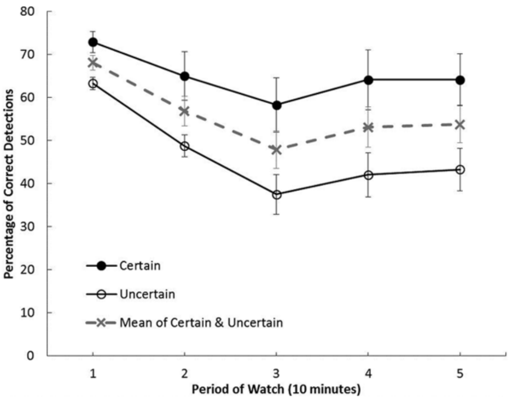

Figure 3. Mean percentages of correct detections in the spatially certain and spatially uncertain conditions as a function of periods of watch. Overall period means are represented by the dashed line. Error bars are standard errors.

CBFV

Control issues. Cerebral hemovelocity values can differ widely across individuals depending on such characteristics as sex and/or age (Adams, Nichols, & Hess, 1992). To control for that variability, the CBFV values for all observers in this study were expressed as a proportion of the last 60 s of their 5-min resting baseline. This baseline index was recommended by Aaslid (1986) and utilized in all of the previous studies of cerebral hemovelocity and vigilance cited earlier. Baseline values for the spatially certain, spatially uncertain, and passive control observers are presented in Table 1.

A 3 (condition) × 2 (hemisphere) mixed-model ANOVA of the baseline data revealed no significant main effects for condition or hemisphere and no significant Condition × Hemisphere interaction, $p > .05$ in all cases. Thus, subsequent CBFV effects involving the two cerebral hemispheres, active and passive observing, and the need to monitor the spatially certain display compared with the spatially uncertain display cannot be attributed to sampling artifacts in the original resting baselines.

Table 2 presents the CBFV scores in terms of proportion of baseline for the passive control observers in regard to cerebral hemisphere and time on task during the experimental session.

It is evident in the table that the CBFV scores in each hemisphere remained at baseline levels throughout the course of the session. A 2 (hemisphere) × 4 (period of watch) mixed-model ANOVA of the data for the passive control observers revealed no significant main effects for hemisphere or periods of watch and no significant interaction between these factors, $p > .05$ for each source of variance, thereby indicating that the hemispheric and temporal differences in CBFV values among the active observers, to be described next, were task related.

CBFV in active observers. Mean blood flow velocity values in the spatially certain and spatially uncertain conditions are plotted as a function of periods of watch in Figure 4. Data from the left and right hemispheres are presented separately in each panel.

A 2 (condition) × 2 (hemisphere) × 5 (period of watch) mixed-model ANOVA revealed that the overall level of CBFV was significantly higher in the right ($M_{right} = 0.98$, $SD_{right} = 0.05$) than in the left hemisphere ($M_{left} = 0.96$, $SD_{left} = 0.04$), $F(1, 22) = 10.77, p < .05, \eta_p^2 = .33$, and that the overall level of CBFV declined significantly across the periods of watch ($M_1 = 1.01$, $SE_1 = 0.01$; $M_2 = 0.99$, $SE_2 = 0.01$; $M_3 = 0.97$, $SD_3 = 0.01$; $M_4 = 0.95$, $SE_4 = 0.01$; $M_5 = 0.94$, $SE_5 = 0.01$), $F(2.48, 54.65) = 49.88, p < .05, \eta_p^2 = .69$. The main effect for task condition and all of the single-order interactions in the analysis lacked significance, $p > .05$ in each case. However, the second-order interaction between condition, hemisphere, and period was statistically significant, $F(3.03, 66.65) = 3.92, p < .05, \eta_p^2 = .15$.

As can be seen in Figure 5, CBFV values in the left hemisphere were similar in the spatially certain and uncertain conditions and declined in a like manner over time in both conditions. By contrast, in the right hemisphere, CBFV values in the spatially uncertain condition were initially slightly higher than those in the spatially certain condition, but dropped off more precipitously over time. Consequently, CBFV scores in the uncertain condition fell below those of the certain condition by the end of the watch-keeping session. These impressions were confirmed by supplementary ANOVAs of the CBFV scores in each hemisphere. The only significant source of variance in the left hemisphere was for periods of watch, $F(2.40, 52.70) = 28.44, p < .05, \eta_p^2 = .56$.

TABLE 1: Mean Baseline CBFV Scores (in cm/s) for Observers in the Active and Passive Control Conditions

	Hemisphere		
Condition	Left	Right	Mean
Certain	57.81 (1.76)	56.13 (1.64)	56.97
Uncertain	55.49 (1.88)	54.71 (1.97)	55.10
Passive control	53.47 (2.70)	51.01 (2.24)	52.24
Mean	55.59	53.95	

Note. Standard errors are in parentheses. CBFV = cerebral blood flow velocity.

TABLE 2: Mean CBFV Scores in the Left and Right Hemispheres During Each Period of Watch for the Passive Control Observers

	Period of Watch (10 Min)				
Hemisphere	1	2	3	4	Mean
Left	0.99 (.01)	0.98 (.01)	0.98 (.02)	1.00 (.01)	0.99
Right	1.01 (.01)	1.01 (.02)	1.00 (.02)	0.99 (.02)	1.00
Mean	1.00	1.00	0.99	1.00	

Note. Standard errors are in parentheses. CBFV = cerebral blow flow velocity.

A follow-up post hoc trend analysis indicated that the effect for periods of watch in the left hemisphere is best represented as a significant linear decline in CBFV over time, $F(1, 22) = 54.80$, $p < .001$, $\eta_p^2 = .72$. In the right hemisphere, the main effect for condition was not significant, $p > .05$. However, there was a significant main effect for periods, $F(2.53, 55.70) = 40.14$, $p < .05$, $\eta_p^2 = .65$, and a significant Condition × Period of Watch interaction, $F(2.53, 55.70) = 5.64$, $p < .05$, $\eta_p^2 = .20$. To examine that interaction more fully, we compared the linear trends in both the certain and uncertain conditions. The trends in both conditions were statistically significant, $F_{\text{certain}}(1, 11) = 39.13$, $p < .001$, $\eta_p^2 = .78$; $F_{\text{uncertain}}(1, 11) = 47.29$, $p < .001$, $\eta_p^2 = .81$. As indicated by polynomial contrasts, there was a significant interaction between the linear trends, $F(1, 22) = 10.60$, $p < .01$, $\eta_p^2 = .32$, indicating that the linear trend in the uncertain condition was significantly steeper than that in the certain condition (Stevens, 1986).

Ocular Activity

PERCLOS index. The mean percentage of time per period of watch that observers in the spatially certain and spatially uncertain conditions met the PERCLOS criterion for eye closure (75% or more closure of both eyes at the same moment) is displayed in Figure 5.

It can be seen in the figure that the percentage of time within each period of watch that the observers' eyes met the PERCLOS criterion was consistently greater in the spatially uncertain than in the spatially certain condition. It is also evident in the figure that this difference was maximized during the latter stages of the vigil, since the PERCLOS scores for the uncertain condition were magnified across the watch-keeping session, whereas they remained relatively stable over the course of the session in the spatially certain condition. These impressions were supported by a 2 (condition) × 5 (period of watch) mixed ANOVA of the data of Figure 5, which revealed significant main effects for condition, $F(1, 22) = 6.83$, $p < .05$, $\eta_p^2 = .24$, and period of watch, $F(2.36, 51.91) = 4.05$, $p < .05$, $\eta_p^2 = .16$, and a significant interaction between these factors, $F(2.36, 51.91) = 2.92$, $p < .05$, $\eta_p^2 = .12$. In regard to the significant Condition × Period of Watch interaction, post hoc trend analyses supported the view that the task differences in PERCLOS scores were magnified over the course of the vigil. In the spatially certain condition, the time course of the PERCLOS scores was essentially flat, as reflected by the absence of

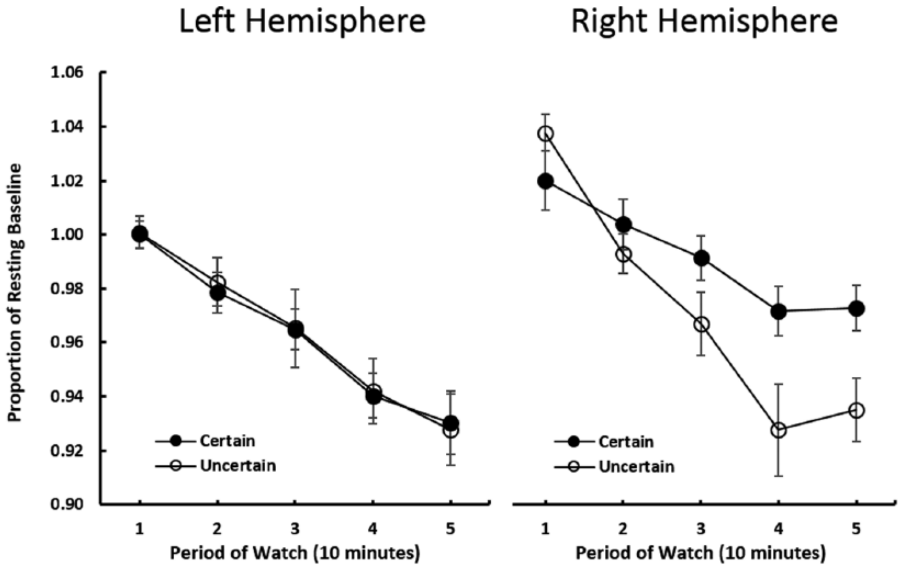

Figure 4. Hemovelocity scores in the left and right cerebral hemispheres for the spatially certain and spatially uncertain conditions as a function of periods of watch. Error bars are standard errors.

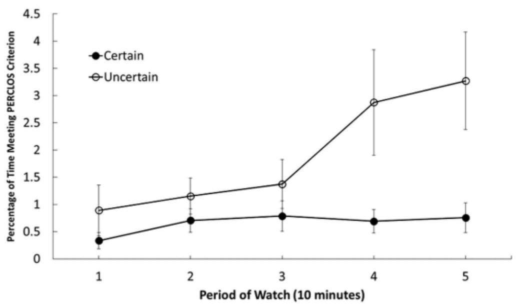

Figure 5. Mean percentage of time observers met the PERCLOS (percentage of eye closure) criterion for the spatially certain and spatially uncertain conditions as a function of periods of watch. Error bars are standard errors.

a significant linear trend, $F(1, 11) = 2.22, p = .16$. However, the trend analysis for the PERCLOS scores in the spatially uncertain condition indicated that the time course of those scores is best represented by a significant linear increase over time on task, $F(1, 11) = 5.76, p < .05, \eta_p^2 = .34$.

DISCUSSION

Consistent with previous findings that spatial uncertainty degrades performance efficiency in vigilance tasks (Adams & Boulter, 1964; Baker, 1958; Bell et al., 1974; Grubb et al., 1995; Helton et al., 2010; Kulp & Alluisi, 1967; Milosevic, 1974; Mouloua & Parasuraman, 1995; Nicely & Miller, 1957), the overall level of signal detections in the present study was significantly lower among observers in the context of spatial uncertainty than in that of certainty.

One goal for the present study was to test the expectation that because of the higher information-processing demands associated with spatial uncertainty, the decline in CBFV over time would be greater when observers were uncertain about where in the visual field events to be inspected for critical signals would appear (spatial uncertainty) than when the events to be inspected occurred in a fixed location (spatial certainty). In accord with previous findings regarding a right-hemispheric system in control of vigilance, it was also anticipated that the CBFV effects associated with spatial uncertainty would be most evident in the right hemisphere.

As anticipated, the temporal decline in CBFV was greater in the presence of spatial uncertainty versus certainty, and the difference between these two spatial conditions was limited to the right hemisphere. Although the hemispheric

results obtained in the present study are consistent with previous findings regarding a right-hemispheric system in the functional control of vigilance (Parasuraman et al., 1998; Warm & Parasuraman, 2007; Warm, Parasuraman, et al., 2008), it is important to note that CBFV in this study also declined over time in the left hemisphere in a similar manner for the spatially certain and uncertain conditions, and that other studies have also shown that the left hemisphere is involved in the performance of vigilance tasks (Funke et al., 2011; Helton, Hayrynen, & Schaeffer, 2009; Hitchcock et al., 2003; Schultz, Matthews, Warm, & Washburn, 2009; Shaw et al., 2012). Evidently, vigilance performance is not completely lateralized. As Hitchcock et al. (2003) and Shaw et al. (2012) have noted, a finding of this sort is consistent with Hellige's (1993) point that both hemispheres may process a given type of stimulus information but in different ways and that a cooperative interaction model (cf. Allen, 1983; Lawrence, Ross, Hoffman, Garavan, & Stein, 2003) may best describe the central mode of functioning in regard to vigilance performance. Evidently, as Hitchcock et al. (2003) and Shaw et al. (2012) have been careful to point out, a determination of the exact task characteristics that give rise to left and right hemispheric dominance in vigilance is an important element for future research.

A second goal for the present study was to compare the effects of spatial certainty/uncertainty on an oculomotor index of fatigue known as the PERCLOS measure. It was anticipated that the PERCLOS index would increase with time on task and that this effect would likewise be greater in the context of spatial uncertainty than certainty. Consistent with the findings of Dinges et al. (1998), the PERCLOS metric increased with time on task, and consistent with expectation, this increase was condition related—it was observed only in the context of spatial uncertainty.

In his development of the neuroergonomic concept, Raja Parasuraman offered it as a means to further understand the information-processing demands of tasks to be performed. This was certainly the case in the present study. Both neuroergonomic measures employed herein, cerebral hemovelocity and the PERCLOS metric, provide strong evidence that when confronted with spatial uncertainty in a vigilance task, observers face a taxing assignment that drains information-processing assets and induces oculomotor fatigue to a greater degree than is the case when spatial uncertainty is not a factor in the task to be performed.

On a theoretical level, the results of this study are broadly consistent with predictions derived from the resource model of vigilance proposed by Raja Parasuraman and Roy Davies (Davies & Parasuraman, 1982; Parasuraman & Davies, 1977) and thereby provide empirical support for that model. Nevertheless, it is important to note that at the present time, the resource model is one of the two dominant theoretical accounts of vigilance performance (Thomson et al., 2015; Warm et al., 2015; Yamaguchi & Proctor, 2015). The other is the mindlessness model proposed by Robertson and his colleagues (Manly, Robertson, Galloway, & Hawkins, 1999; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997). According to that view, the repetitive and monotonous nature of vigilance tasks leads a supervisory attention system to lose its potency and thereby to a mindless lack of attentional focus, perceptual decoupling from the task at hand, and consequent failures of signal detection.

On the basis of the mindlessness model, one might speculate that the poorer performance and greater temporal decline in CBFV in the context of spatial uncertainty relative to spatial certainty in the present study reflect a greater degree of perceptual decoupling in the former than in the latter case. That possibility seems unlikely, however. The need to monitor stimulus events that appear in an unpredictable rather than a predictable location would seem to enhance stimulus variation in the spatially uncertain as compared with the spatially certain condition and therefore might be expected to minimize the level of perceptual decoupling in the spatial-uncertainty relative to the spatial-certainty case.

Moreover, two experimental findings lead one to expect that in the absence of task-related information processing, CBFV would return to baseline levels rather than remain below baseline as they did in this study. The first source of evidence for this expectation comes from the participants assigned to the passive control condition in this

study, whose CBFV scores remained at baseline levels throughout their 40-min experimental session as they observed the vigilance display without the need to make signal/noise discriminations. The second is a recent finding in this laboratory that CBFV scores return to baseline levels within 30 s after active observers complete a vigilance task and are therefore decoupled from the task (Dillard, Warm, Funke, & Nelson, 2013). In addition, the finding that oculomotor fatigue as reflected in the PERCLOS index increased over the course of the vigil, particularly in the spatial-uncertainty condition, is inconsistent with the argument that the results of this study stem from perceptual decoupling. In our view, the present results are more compatible with the resource than with the mindlessness model.

In addition to fostering an understanding of the neurophysiological elements underlying the effects of psychophysical factors in vigilance on a basic science level, the neuroergonomic approach also has operational implications in that it seeks to enhance neurophysiological diagnosticity in determining when operators in tasks requiring high levels of vigilance are in need of rest or replacement (cf. Reinerman-Jones et al., 2016; Warm, Parasuraman, et al., 2008). For example, CBFV may be useful in contexts where responses are infrequent and behavioral metrics are unreliable or when observers try to compensate for loss of resources through strategic changes (Matthews et al., 2000). In this regard, recent studies have shown that combining neurophysiologic indicators improves the detection of mental fatigue (Chai et al., 2015; Laurent et al., 2013). Accordingly, given that temporal declines in signal detection during a vigilance task are accompanied by declines in CBFV and increments in eye closure (PERCLOS), these measures might be combined into a test battery to alert supervisory personnel when the ability of operators to perform their assigned vigilance tasks is excessively compromised by mental fatigue. In terms of the operational utility of CBFV scores in vigilance, a diagnostic effort along this line would blend well with selection studies by Matthews and his associates demonstrating that combining CBFV with a self-report measure of mental fatigue on a demanding, short pretest identifies individuals who will be most susceptible to the vigilance decrement (Matthews et al., 2010; Reinerman-Jones, Matthews, Warm, & Langheim, 2011).

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KEY POINTS

- Spatial uncertainty degraded signal detection in a visual vigilance task.
- A temporal decline in cerebral blood flow velocity (CBFV) in the right hemisphere was greater in the presence of spatial uncertainty versus certainty.
- In the left hemisphere, CBFV declined over time in a similar manner in both spatial conditions, indicating that CBFV changes were not completely lateralized to the right hemisphere.
- Eye closure as reflected in the PERCLOS index increased with time on task in the spatially uncertain but not the spatially certain condition.
- The neuroergonomic measures employed herein provide strong evidence that spatial uncertainty in the performance of a vigilance task drains the information-processing assets of observers and induces oculomotor fatigue to a greater degree than when spatial uncertainty is not a factor in the task to be performed.

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